10

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The Effect of Initial Head Pitch and Subject Size on Head X-Acceleration and Head/Neck Rotation during +Gz Impact Acceleration

E. M. Yliniemi, M. Ziejewski, and C. E. Perry

ABSTRACT

When a person is subjected to +Gz impact acceleration, body anthropometry, initial head orientation, and other experimental factors can influence the response of the human head/neck. To predict head/neck response, the significance of these factors must be explored. This paper evaluates the influence of the initial head pitch, subject mass, and sitting height on head x-acceleration and head/neck rotation reference points (occipital condyle and first thoracic vertebra). The data used for this evaluation came from two experimental studies conducted on a vertical deceleration tower (VDT) at the Air Force Research Laboratory (AFRL), Wright-Patterson Air Force Base, Dayton, Ohio. The data includes 138 tests conducted on 27 subjects—15 male and 12 female. Human subjects were exposed to vertical accelerations from 6 G to 10 G. The 10 G impacts provide biodynamic responses comparable to those encountered during the catapult phase of an ACES II ejection. In this evaluation, subjects wore identical helmets; however, trends identified are applicable to any test condition where subjects experience positive vertical impact acceleration, including scenarios without helmets. Statistical analysis shows that initial head angle is highly significant for determining the location of primary head/neck rotation. It also indicated that initial head angle, subject mass, and sitting height are significant factors when predicting head x-acceleration. A predictive tool for determining the location of primary rotation has been developed. This tool is based on the initial head angle, subject mass, sitting height, and the interaction between sitting height and subject mass.

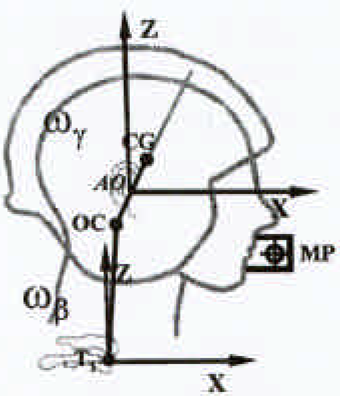
INTRODUCTION

Air Force Research Laboratory (AFRL) has conducted several research programs evaluating the effects of vertical impact acceleration on human head/neck response. High-speed film footage shows that for identical test conditions, some subjects respond with neck flexion, while others display neck extension (Ziejewski et al., 1999).

When assessing the potential for head/neck injury, one must consider many parameters including, but not limited to, magnitude, duration, direction, and location of internal forces. Knowing the direction and location of internal forces may be important because of the following two known facts: (1) the neck is at least three times stronger in resisting flexion than extension and (2) the load-carrying ability of the cervical portion of the spine tends to increase, progressing from the upper cervical toward the thoracic region (Mertz and Patrick, 1971 and Yoganandan et al., 1989). Consideration must also be given to the cumulative effect of head/neck system geometry and the duration of head/neck response; both can be assessed using the magnitude of head x-acceleration.

Rotation Reference Points

From kinematic analysis of the head/neck system, a two-pivot linkage mechanism can represent the head/neck anatomical structure as shown in Figure 1. Considering this linkage system, one can identify two rotation reference points—the head pivot (OC) and the neck pivot (T_1).



OC - Occipital Condyle Point (Head Pivot)
CG - Head Center of Gravity
AO - Anatomical Origin
T_1 - First Thoracic Vertebra (Neck Pivot)
MP - Mouth Piece

Figure 1. Schematic diagram of head/neck structure.

Modes of Vertical Impact

Five modes of human head/neck response to vertical impact have been identified (Ziejewski et al., 1999). Table 1 shows the modified portion of a table describing the modes presented by Ziejewski et al. Modes A and B display forward head rotation, modes C and D demonstrate rearward head rotation, and mode E is characterized by minimal head rotation (primarily vertical translation). Additionally, three major categories of factors influencing the head/neck response were suggested including initial head/neck position and body anthropometry; however, they were not fully quantified.

Table 1. Modified Modes of Head/Neck Response for Vertical Impact.

		MODES				
		A	B	C	D	E
	Head Rotation (γ)	Forward	Forward	Rearward	Rearward	Minimal
	Condition*	$\omega_\beta > \omega_\gamma$	$\omega_\beta < \omega_\gamma$	$\omega_\beta > \|\omega_\gamma\|$	$\omega_\beta < \|\omega_\gamma\|$	N/A
DIAGNOSTIC PARAMETERS	X-Acceleration *(Initial at Mouthpiece)*	+	-	+	-	+/-
	Head Pitch *(Mouthpiece wrt ear)*	-	-	+	+	Minimal

*ω_β = angular velocity of neck, ω_γ = angular velocity of head

Objectives

The three main objectives of this study were to assess the effects of 1) initial head pitch on the magnitude of head x-acceleration; 2) initial head pitch on the location of primary head rotation; and 3) subject body mass and sitting height on head/neck kinematics.

METHODS

Experimentation

The Vertical Deceleration Tower (VDT) facility at AFRL was used to conduct the experiments in this evaluation. The VDT is composed of an impact carriage mounted on two vertical guide-rails identified (Perry et al., 1997). The test assembly, including a generic ejection seat, a restraint harness, and instrumentation, is mounted to the impact carriage. The carriage is raised and free-falls along the vertical rails onto a water reservoir (hydraulic decelerator) at the base of the tower. A contoured piston mounted on the bottom of the carriage is guided into the reservoir where the displacement of the water around the piston decelerates the carriage and produces an upward (+Gz) acceleration. The subjects are placed in the VDT seat in an upright position and restrained with a standard double shoulder strap and lap belt combination. Principal measured parameters include tri-axial linear accelerations at the head (mouthpiece) and chest, head and chest angular accelerations about the lateral axis, seat and carriage vertical (z-axis) accelerations, and seat pan loads.

Test data was selected from two studies: Evaluation of the Effects of Gender and Anthropometry on Human Dynamic Response During +Gz Impact Acceleration and B-2 Seat Cushion Tests (199602), part of the Female Impact Program (FIP), and Investigation of Biodynamic Characteristics of the Chest and Thoracic Spine During +Gz Impact (199405). The data was chosen based on helmet type, absence of other equipment, and number of tests per subject. All subjects wore a standard HGU-55/P helmet, but did not wear other equipment such as oxygen masks, night-vision goggles, or helmet-mounted displays. Although physical characteristics of the helmet may affect the magnitude of head acceleration and the extent of head rotation, trends identified in this study are applicable to any test condition where subjects experience negative vertical acceleration, including scenarios without helmets. To observe the effects of initial test parameters on an individual subject, tests were selected only if four or more tests, meeting the above criteria, were available for a given subject. Nominal carriage accelerations ranged from 6G to 10G.

Human Subjects

A total of 138 tests using 27 subjects, both male and female with body masses between 49.9 kg (110 lb) and 103.4 kg (228 lb), were chosen based on the selection criteria. Table 2 lists each subject's identification, gender, mass (kg), height (mm), sitting height (mm), and the number of tests observed for this evaluation. Body anthropometry for each subject was measured prior to participation in the impact experiments.

Head Pitch Measurement

Body displacements during impact were measured using a SELSPOT infrared detection system. The initial head pitch was found using body displacements by calculating the angle between the helmet-ear (1) and the mouthpiece (2) with respect to a plane parallel to the seat pan (clockwise angle is negative). Figure 2 shows the angle as gamma (γ). The head pitch for a person looking straight-ahead (approximately when the head anatomical x-axis is parallel to the seat pan) is around $-10°$.

Table 2. Subject Anthropometry.

Subject ID	Gender	Mass* (kg)	Height (mm)	Sitting Ht. (mm)	Number of Tests
R-20	F	49.9	1615	878	4
V-3	F	53.1	1622	859	6
S-20	F	56.7	1712	860	6
W-8	F	57.2	1697	890	7
B-16	F	57.6	1658	895	4
J-9	F	58.5	1555	814	4
C-15	F	58.5	1614	871	4
L-11	F	60.3	1647	857	5
B-17	F	61.2	1702	885	6
K-9	F	62.1	1673	866	5
O-5	F	63.5	1665	892	4
O-3	M	65.3	1589	844	5
M-21b	M	68.0	1674	867	5
J-11	F	70.3	1669	876	5
C-17a	M	72.6	1772	964	4
J-7	M	74.8	1719	905	5
Y-1	M	75.3	1747	916	4
G-11	M	78.5	1766	934	7
H-15	M	79.4	1757	907	4
M-30	M	81.6	1779	945	5
C-12	M	83.0	1729	930	6
P-11	M	84.4	1880	963	4
J-10	M	87.5	1754	925	6
S-11b	M	93.9	1810	933	6
E-4	M	99.3	1816	975	5
R-21	M	102.1	1811	968	6
B-11	M	103.4	1847	952	6
		Total Number of Tests			138

*Average mass for tests considered

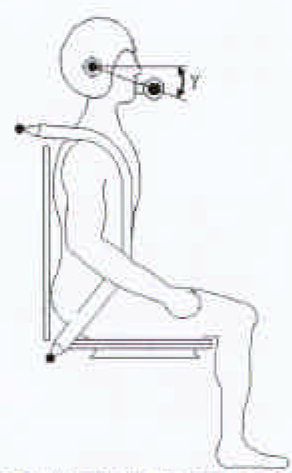


Figure 2. Head pitch angle definition.

Figure 3 shows a frame from high-speed film just prior to impact for six different tests performed on a male subject (G-11). The calculated initial head angle is displayed beneath each image. Initial head angles for this subject varied from –17.5° to –3.2°. Therefore, a subject does not necessarily brace/position himself/herself the same way prior to impact for each test.

RESULTS

Modal Response

Each test was categorized into its appropriate mode (A, B, C, D, or E). Modes A and C have positive initial x-accelerations at the mouthpiece, while modes B and D have negative initial x-accelerations. Due to geometrical constraints of the experimental setup and the physiological characteristics of the head/neck, the neck pivot (T_1) is the primary center of rotation when the primary head x-acceleration is positive. Conversely, when the primary head x-acceleration is negative, the primary center of rotation is the head pivot (OC).

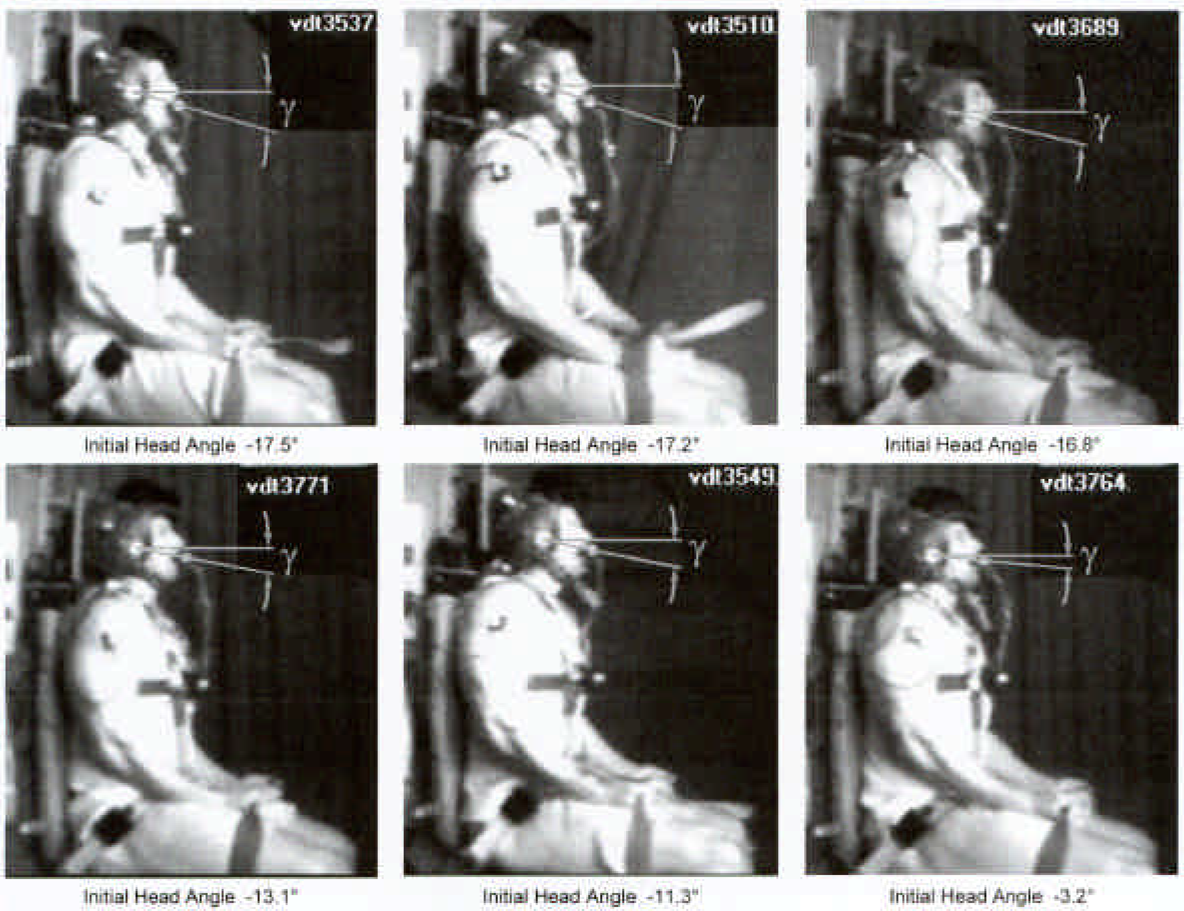


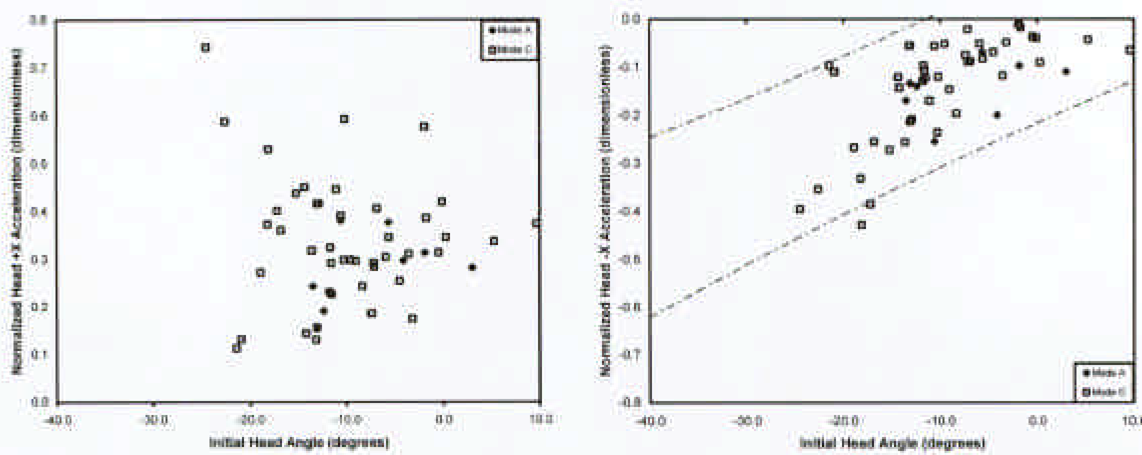
Figure 3. Subject G-11 initial head positions.

In this paper, primary acceleration is defined as the first well-defined head acceleration peak. Normalized head x-acceleration (calculated by dividing head x-acceleration by the input carriage acceleration) is plotted versus initial head angle in Figures 4 through 6. When a general trend was observed in the data, a 95% prediction band (based on linear regression analysis) is shown with dashed lines. This band depicts the region where 95% of the data points will likely fall. As the correlation coefficient for the data improves, the prediction band becomes tighter.

Modes A and C are plotted in Figure 4, and modes B and D are plotted in Figure 5. Although Modes A and C and modes B and D have head rotation in opposite directions, they are evaluated together because they have the same primary center of rotation. The location of primary rotation for modes A and C is at the neck pivot, whereas it is at the head pivot for modes B and D. The first chart (a) in each figure shows the primary accelerations for each mode and (b) displays the rebound acceleration.

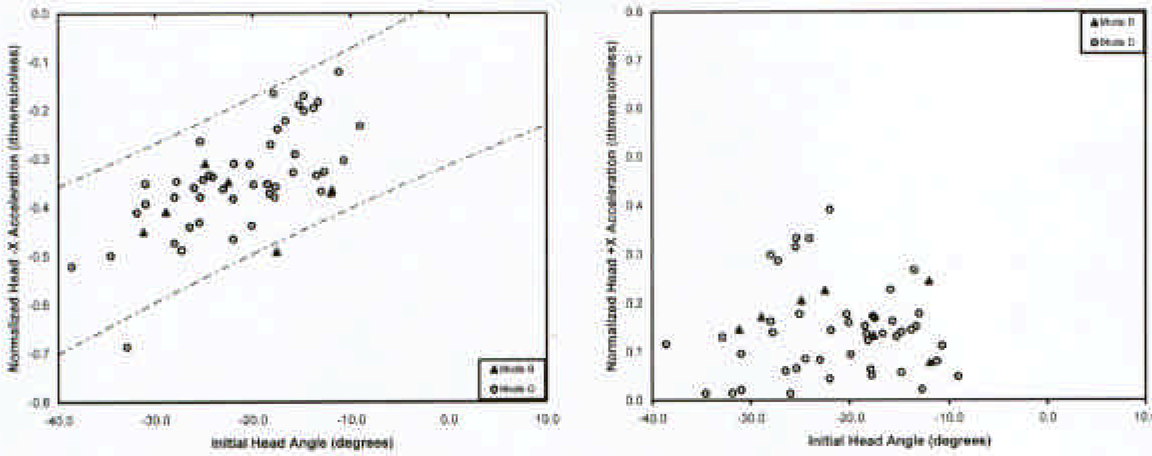
Based on the data in Figures 4 and 5, the rebound acceleration has a smaller magnitude than the primary acceleration, as expected. It appears that the normalized negative x-acceleration (Figures 4b and 5a) correlates to the initial head angle better than the positive x-acceleration (Figures 4a and 5b) regardless if it is the primary or rebound acceleration. Note that in these figures the majority of points for modes A and C lie on the right-hand side of the plot and for modes B and D the points are on the left-hand side. The mean initial head angle for modes A and C is –9.7° and for modes B and D is –21.3°. Recall that the commonality for modes A and C is that the primary center of rotation is at the neck pivot and for modes B and D it is at the head pivot. Therefore, it seems that as the initial head angle becomes more negative (<-20°), the location of primary rotation is at the head pivot. When the initial head angle becomes more positive (>-10°), primary rotation is likely to occur at the neck pivot.

Another significant observation from Figures 4 and 5 is that the number of tests falling into modes A and B is less than the number of those in modes C and D. Modes A and B are characterized by forward head rotation and modes C and D display rearward head rotation. Out of the total 138 tests, only 15 (10.9%) had forward head rotation, while 33 (23.9%) had minimal head rotation, and 90 (65.2%) showed rearward



a. Primary (positive) b. Rebound (negative)

Figure 4. Modes A and C (primary center of rotation at neck pivot) normalized head x-acceleration.

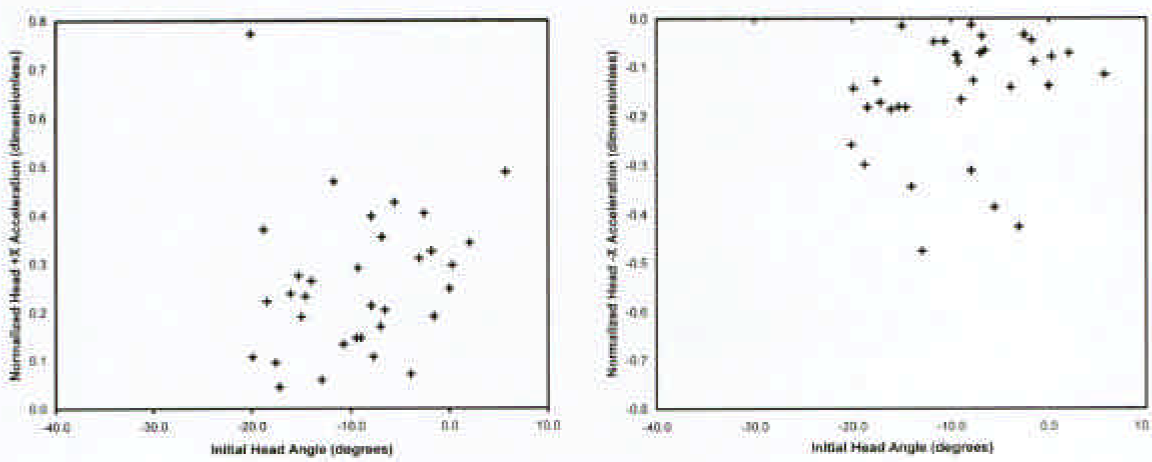


a. Primary (negative) b. Rebound (positive)

Figure 5. Modes B and D (primary center of rotation at head pivot) normalized head x-acceleration.

head rotation. Although statistical analysis of the data used in this investigation indicates that the initial head angle is significant in determining the location of primary rotation, it did not identify a significant correlation between the initial head angle and the direction of head rotation. Factors that may have even more influence on head rotation, other than initial head angle or subject mass, is subject preparedness/ bracing and neck strength. However, bracing and neck strength are factors that are very difficult to measure (Morris, 1996).

Finally, mode E is shown in Figure 6. For mode E, the primary x-acceleration can be either positive or negative, so primary and rebound accelerations are plotted together. The plots for mode E show that although head rotation is minimal, head x-acceleration is not necessarily minimal. In Figure 6 the points tend to be toward the right-hand side of the plot with a mean initial head angle of –9.2°.



a. Positive b. Negative

Figure 6. Mode E normalized head x-acceleration.

Table 3. Initial Head Angle and Primary Rotation Reference Point.

Initial Head Angle	Neck Pivot		Head Pivot	
	No.	Percent	No.	Percent
0° to 10°	8	100%	0	0%
-5° to 0°	12	85.7%	2	14.3%
-10° to -5°	17	81.0%	4	19.0%
-15° to -10°	23	63.9%	13	36.1%
-20° to -15°	10	38.5%	16	61.5%
-25° to -20°	5	33.3%	10	66.7%
-30° to -25°	0	0%	11	100%
< -30°	0	0%	7	100%
Total	75	54%	63	46%

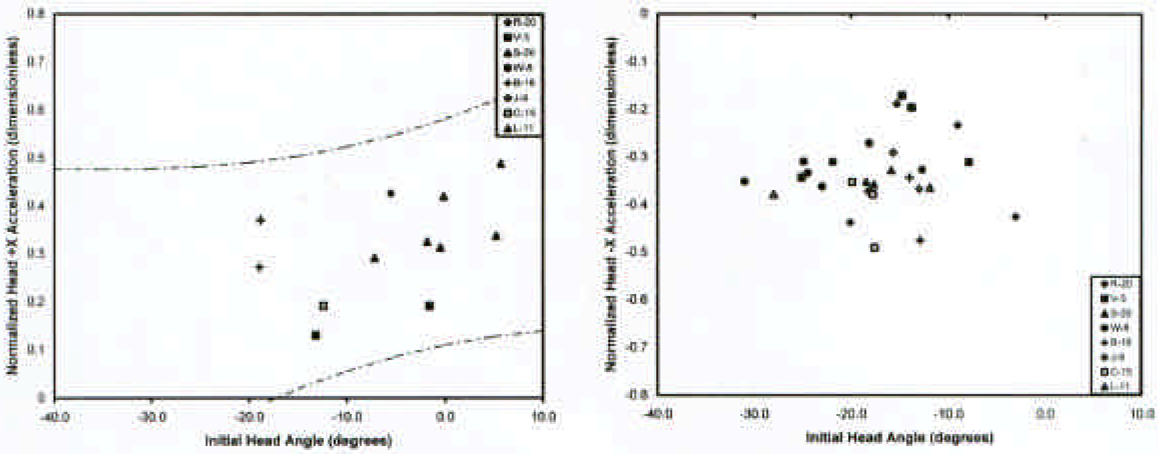
Of the 138 tests, the primary center of rotation was at the neck pivot for 75 tests (54%) and at the head pivot for 63 tests (46%). The mean normalized x- acceleration for tests with primary rotation at the neck pivot was 0.325 and –0.331 at the head pivot. Comparing magnitudes, one finds they are not significantly different. Although the head x-acceleration magnitudes are the nearly same, they may have very different effects, with respect to injury potential, depending on whether primary rotation occurs at the head pivot or the neck pivot. The same head x-acceleration magnitude will not be as significant for rotation primarily at the neck pivot when compared to rotation primarily at the head pivot. This is because the neck is able to resist loads better in flexion than extension and the upper portion of the neck is not as strong as the lower portion.

Influence of Subject Mass on Head/Neck Response

The tests were also categorized into three mass classes—under 61.2 kg (135 lb), 61.2 kg (135 lb) to 81.2 kg (179 lb), and 81.6 kg (180 lb) and greater. Figures 7 through 9 show primary normalized x-accelerations for each body mass class. Part a of each figure shows the tests with the primary center of rotation at the neck pivot and part b at the head pivot. Again, when a trend was observed, a prediction band is shown. Different markers are used to distinguish subjects.

Figures 8a and 9a show that the primary normalized x-acceleration, for subjects with masses greater than 61.2 kg (135 lb), do not correlate with the initial head angle when the primary center of rotation is at the neck pivot. However, Figure 7a shows that there may be a slight positive correlation for subjects with masses less than 61.2 kg (135 lb).

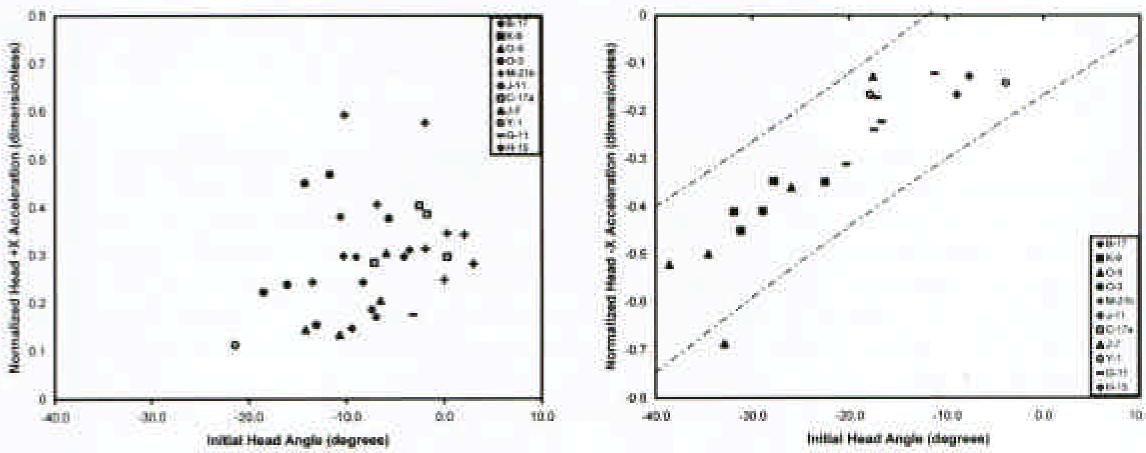
When the head pivot is the primary center of rotation, a general trend between the primary normalized x-acceleration and initial head angle for subjects with masses less than 61.2 kg (135 lb) is not observed. Nevertheless, a definite trend is observed for subjects with masses between 61.2 kg (135 lb) and 81.2 kg(179 lb). As can be seen, when the initial head angle becomes more negative, the x-acceleration also becomes more negative. This trend can also be observed for subjects with masses more than 81.6 kg (180 lb), but the correlation is not as good. Analyzing the data per subject reveals that an individual subject tends to have the same primary center of rotation for multiple tests.



a. Primary center of rotation at neck pivot.

b. Primary center of rotation at head pivot

Figure 7. Normalized head x-acceleration for subjects with masses less than 61.2 kg (135 lb).



a. Primary center of rotation at neck pivot.

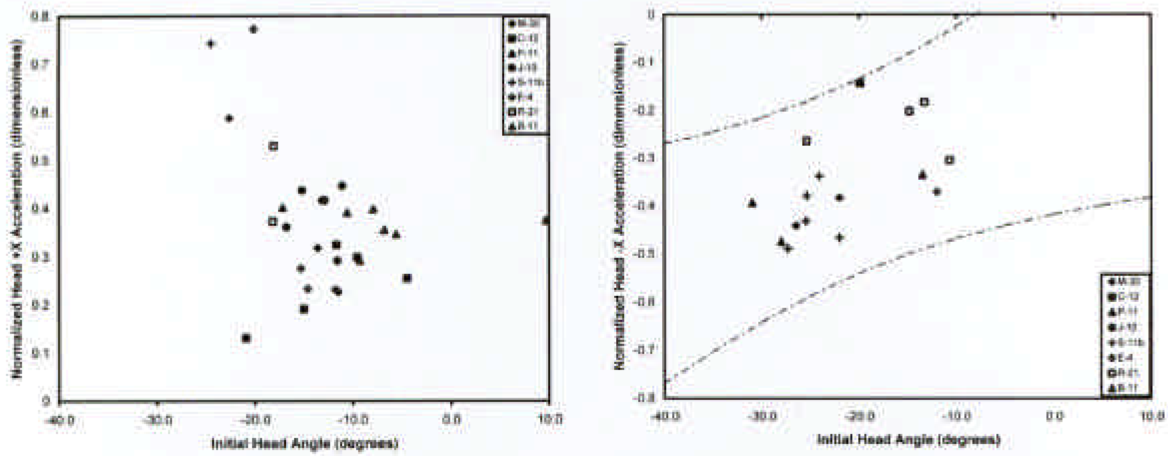
b. Primary center of rotation at head pivot.

Figure 8. Normalized head x-acceleration for subjects with masses from 61.2 kg (135 lb) to 81.2 kg (179 lb).

Regression Model

A regression model, analyzed in SAS/STAT®, was used to evaluate the significance of independent variables, initial head angle, mass, sitting height, and subject size (interaction between mass and sitting height) on the dependent variable, normalized x-acceleration. All independent variables had significance levels of at least 10% having the following significance values: initial head angle (Pr>|T|=0.0001), subject mass (Pr>|T|=0.0310), sitting height (Pr>|T|=0.0829), subject size (Pr>|T|=0.0450) and intercept (Pr>|T|=0.0689). These results show that, for the independent variables evaluated, initial head angle and subject mass are the most significant factors for predicting head/neck response. The regression equation for this model is

$$Y = 0.0234X_1 + 0.0996X_2 + 6.05\text{E-}3X_3 - 9.91\text{E-}5X_4 - 5.80$$



a. Primary center of roation at neck pivot.

b. Primary center of rotation at head pivot

Figure 9. Normalized head x-acceleration for subjects with masses greater than 81.6 kg (180 lb).

where, Y_1 is the Head x-acceleration, X_1 is the Initial Head Angle (degrees) , X_2 is the Subject Mass (kg), X_3 is the Subject Sitting Height (mm), and X_4 is a body size defined as interaction between mass and sitting height.

This equation compliments the predictive capability of the initial head angle that was stated earlier. The initial head angle predicts the center of head/neck rotation when it is less than –20° and greater than -10°, however this technique does not predict the primary center of rotation between –20° and –10°. In this region, one can use the regression equation, which is based on parameters in addition to the initial head angle including subject mass, sitting height, and the interaction between subject mass and sitting height. When Y is positive, primary rotation occurs at the neck pivot, and when Y is negative, rotation is primarily at the head pivot. These predictive tools for determining the location of primary rotation are summarized in Table 4.

CONCLUSIONS

1. Initial head angle, subject mass, sitting height, and body size (the interaction term between mass and sitting height) have been shown to be statistically significant factors for predicting magnitude and direction of head x-acceleration.

2. Initial head angle is a highly significant factor for predicting the location of primary rotation.

3. It appears that as the initial head angle becomes more negative (<-20°), the location of primary rotation is at the head pivot. When the initial head angle becomes larger (>-10°), primary rotation most likely occurs at the neck pivot. A regression equation was developed for predicting the primary center of head/neck rotation in the region between –20° and –10° using additional factors such as mass and sitting height.

Table 4. Predictive Tools for Determining Primary Center of Rotation.

		Primary Center of Rotation	
		Neck Pivot	**Head Pivot**
DIAGNOSTIC PARAMETER	**X-Acceleration** *(Initial at Mouthpiece)*	+	-
	Initial Head Angle* *>-10° or <-20°*	> -10°	< -20°
		Y > 0	Y < 0
PREDICTIVE TOOLS	**Initial Head Angle*** *between –20° and –10°*	$Y = 0.0234X_1 + 0.0996X_2 + 6.05E\text{-}3X_3 - 9.91E\text{-}5X_4 - 5.80$ Y = Head x-acceleration X_1= Initial Head Angle (degrees) X_2= Subject Mass (kg) X_3= Subject Sitting Height (mm) X_4= X_2X_3 (Interaction between mass and sitting height)	

*Mouthpiece with respect to ear

4. If rotation at the neck pivot is more desirable than at the head pivot, the recommended initial head position should be the following: looking straight-ahead or upward (initial head angle greater than -10°).

5. The difference between x-acceleration magnitude mean values, at both centers of rotation, is statistically insignificant. However, due to anatomical differences in the neck structure, the effect of the accelerations will be different depending on the location of primary rotation and whether the neck responds in flexion or extension.

6. Statistical analysis did not reveal a significant correlation between the initial head angle and direction of head rotation (forward or rearward) i.e. whether the neck responds in flexion or extension. Additional research is needed to determine which factors influence the direction of head rotation.

7. Subjects with masses less than 61.2 kg (135 lb) tend to behave differently in comparison to subjects of greater mass. Therefore, it is likely that other factors are influencing the response of the lighter subjects. More research is needed on these subjects to determine these factors.

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